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A review: The analysis of fires in Chinese historic building and research progress on the fire protection

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ABSTRACT

Historic buildings have significant cultural, scientific, and aesthetic value, and show the accomplishments of past eras. Unfortunately, many historic buildings are being destroyed by fires across the world. Currently, wooden historic building fires occur frequently in China without effective fire control measures. To clarify the current characteristics of these buildings in China, the present work comprehensively investigates fire disaster data from the past ten years and then discusses the main causes of fires and their fire characteristics. In addition, the research progress on the corresponding fire protection, damage evaluation, restoration, and prospect are also discussed. The analysis has concluded that the primary causes of fires are related to electrical factors, careless use of fire, and arson. Fire protection measures and management suggestions are then provided for Chinese wooden historic buildings.

1. Introduction

Historic buildings have profound historical and practical significance, and are an essential part of a society's cultural heritage. In China, there are numerous historic buildings distributed across the territory [1] and because of their non-renewable nature, they have incomparable historical and cultural values. Additionally, as the physical carrier of Chinese cultural heritage, historic buildings contain rich material and spiritual values [2,3]. However, fires in Chinese historic buildings have been happening frequently due to their combustible materials and fire load. Differing from the western historic buildings where stones is often the main structural material, Chinese historic buildings are mainly wooden structures, which have higher fire frequency and risk after years of weathering. Historic building fires pose a serious threat to the protection and preservation of buildings and the life safety of surrounding residents. Therefore, to better understand the main fire protection issues in these historic buildings, it is necessary to analyze the impacts of past fires and explore the progress of the research dealing with fires in historic building.

According to official statistics, 4291 historic buildings are recognized by the government during the past 50 years from 1961 to 2015 [1]. In general, Chinese historic buildings are dominated by wooden structures, supplemented by bricks, tiles, and stones. The construction materials mainly include wood, soil, stone, bricks, tiles, bamboo, etc. among which wood is the most widely used. Over time, the timber of buildings has undergone serious deterioration. Compared with ordinary timber, the weathering timber of historic buildings is much easier to be ignited due to the loss of water [4]. A recent example of this situation was the April 15, 2019, fire accident that occurred at the Notre Dame Cathedral in France. Among other impacts, the fire destroyed most of the wooden components of the roof of the church, toppled the Gothic spire and weakened the overall structure, resulting in incalculable fire losses. Since then, fires in historic building have received extensive media and social attention, and scholars around the world have been conducting in-depth research on fires in older building addressing multiple aspects.

Past research on the fire protection of historic buildings has addressed a number of relevant issues. Based on the analysis of the fire protection situation of historic buildings in China, potential fire protection methods have been proposed [2]. Recently, current fire management approaches, design codes, and especially the actual fire

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protection effectiveness of the codes for historic buildings in the United States were combed and summarized [5]. For heritage villages, fire hazards were investigated according to fire protection experience and fire vulnerability was assessed by measuring the moisture content of wood [6]. The evaluation methods of fire hazard levels were offered taking into account the various influencing factors of safety system engineering [7]. To objectively evaluate the fire risks and fire protection levels, quantitative rather than qualitative methods are often used. For example, semi-quantitative methods were used to assess the fire risks for a historic building called the Potala Palace in Lhasa in the Tibet Autonomous Region [8]. A systematic and quantitative emergency assessment methodology was proposed for evaluating the accessibility of specific fire-fighting techniques to mitigate fire hazards in historical towns [9]. To sum up, the available research on historic building fires mainly focuses on the protection for potential fire risks and emergency treatment methods.

The statistical analysis of fire in ancient building has also been carried out to obtain a more in-depth knowledge of their fire protection issues. The cases of far-reaching fires in foreign history were sorted out, and the most likely cause of the fire was concluded to be the repair and construction of ancient buildings [10]. By reviewing and comparing official evaluation documents, including standards, guidelines, and procedures, past research has also emphasized the gaps and limitations in existing tools [11]. Similarly, after reviewing data on historic building fires in different countries that occurred from 1993 to 2020, the entire fire process, fire causes, and plans for the future reconstruction of Notre Dame were analyzed [12]. Although several scholars have conducted in-depth research on fires in ancient buildings, the number of statistical analyses and research that was carried out addressing these issues is still small. This means that relevant statistical data is often largely unavailable and that the analysis of real fire cases in wooden historic building is not performed. Overall, this implies that current research outcomes on these issues lack generalization.

According to the research and exploration of previous scholars on ancient building fires, this paper probes into the current fire risks, quantitatively investigates the relationship between past fire causes and loss damage, uses Grey relational analysis (GRA) to discuss the fire hazard factors for compensating the research gap and improving the fire safety level. At the same time, the current research progress of wooden historic building fires from the perspective of fire detection and early warning, fire-fighting, and post-disaster repair is also discussed, containing the future research direction.

2. The analysis of past fires in Chinese wooden historic buildings

The statistics and fire causes of past events that occurred in historic buildings in China are described in this section. Based on the characteristics of Chinese ancient buildings, the relationship between the number of fires and their distributions across time, the variation in the number of fires across the years, the causing factors, the direct losses, and the burned-out areas are analyzed. The relationship between the fire causes and the fire severity is quantitatively analyzed using the Grey Relational Analysis method, and several fire cases are listed according to typical causing factors.

2.1. Analysis of the factors that lead to fires in historic buildings

2.1.1. Features of Chinese historic buildings

Chinese historic buildings mostly use wooden frames as the main structure, and involve various architectural styles that are compatible with this structure. This kind of structure mainly builds a wooden structural frame with wooden beams and pillars and then uses other materials as the enclosure/infill structure. There are many types of Chinese wooden frame buildings. Single buildings include halls, penthouses, buildings, pavilions, and so on. The courtyard is composed of these single buildings and is then used as a unit to form diverse architectural groups. In terms of courtyard layout techniques, a balanced and symmetrical approach is generally adopted, along the vertical and horizontal axes. There are also large-scale symmetrical layout buildings, such as the Forbidden City in Beijing. Overall, past fires in historic building and their impacts were found to be particularly related to the following building features:

(1) Materials

Most of the historic buildings in China use wooden frame structures and the main load-bearing elements are wooden beams and pillars. These wooden structures are especially dry after hundreds of years of weathering, and many of them are covered with decorative paintings, which are known to play a negative role in fire protection and prevention [13]. According to the research by Chorlton [14], the carbonization rate of historical wood that is about 150 years old is 20 % faster than that of contemporary wood. Thus, the various wood components in ancient buildings have sufficient conditions for burning and spreading flames. From a fire load perspective, Li [15] found that the fire load of historic buildings in Beijing is dominated by immovable fire loads, and the maximum fire load of 4223.6 MJ/m^2 is almost three times the minimum value of 1418.6 MJ/m^2, which is significantly different from that of conventional modern buildings. Once a fire occurs, since the roof is an immovable fire load, it will cause the smoke and heat in the building to be difficult to dissipate in the event of a fire, and the temperature will quickly accumulate up to a flash point. As the large surface area of the beams, columns, rafters, and the presence of wood cracks and splicing gaps, most of them provide good conditions for ventilation. After the fire, the flame spreads drastically. The burning is violent that is easy to form three-dimensional combustion. Because of the flammability and low fire resistance rating of the existing materials, as well as the large overall fire load, historic buildings are prone to significant fire spreading once a fire occurs, which usually results in irreversible losses.

(2) Building layout

Most of the ancient buildings in China have a symmetrical layout, which is particularly conducive to fire spread. The building complexes with large scale are all connected by corridors, while many buildings with crowded layouts have almost no fire isolation. Since the roof is a major feature of the buildings, such large roofs are also more susceptible to the threat of fire serving as a possible location for fires, as it can provide sufficient oxygen. The impressive Notre-Dame Cathedral fire started at the wooden beams under the roof, and led to the destruction of two-thirds of the roof [12]. Therefore, the overall layout and internal structure of the building not only influences the size of the fire load, but also how fast the fire will spread across the vulnerable elements.

(3) Function and purpose

Historic buildings are mainly used for tourism and religious functions. Due to the huge number of tourists that visit many historic buildings in China, the unsafe behavior of people can become a direct factor in the occurrence of fires. In addition, due to religious factors, most buildings have combustible decorations such as drapery and streamers, while activities such as burning incense, lighting candles and providing permanent lights in the interior also increase the fire risk. Therefore, the existence of numerous long-term fire sources not only increases the difficulties in fire management but also makes the fire detection more difficult.

(4) Geographical location

Many ancient buildings in China are located on remote mountains.

To make full use of the terrain, they were built on steep slopes with winding roads and far away from current fire departments. Once a fire breaks out, it is difficult for rescue teams to reach the scene quickly. For example, the temples of Wutai Mountain, Emei Mountain, Jiuhua Mountain, Putuo Mountain, the Taoist temples of Wudang Mountain, and the Potala Palace in Tibet are all in mountainous areas or on slopes. In mountainous areas, the roads are rugged and narrow. Yuan et al. [6] pointed out that only 10 % of the roads in the heritage village they analyzed were accessible to fire trucks. This points to the fact many roads in remote areas are unable to provide adequate conditions for fire emergency access. As a result, it is very difficult to put out fires when the geographical location creates additional barriers. In addition, some historic buildings in China were built in areas lacking water. Historic buildings in these places are sparsely populated and there is no effective water source for firefighting. In addition, the fire protection facilities in the buildings are not adequate which facilitates small-scale fires to easily develop into large-scale fires. Therefore, the remote location of buildings, the narrow roads, the lack of water sources for firefighting, and the unsatisfactory fire protection facilities are all important factors that, from a geographical location perspective, can lead to more frequent occurrence of larger fires in historic buildings.

2.1.2. Fire development trend analysis

In the current work, a qualitative statistical analysis (QSA) method is first employed to discuss the fire risk of recent years based on 709 fire cases that occurred between 2000 and 2017 in historic buildings in China. The data is from the fire protection yearbooks of China [16] and the literature.

The relation between the number of fires and the months where they occurred is shown in Fig. 1. When analysing these data, it is found that fires in historic buildings occur more frequently in January, April, November, and December, i.e. fires mainly occur predominantly in winter and in spring. From these results, it is inferred that this distribution of fires across the months can be related to Chinese religious activities and traditional festivals such as the Qingming Festival in spring or the Spring Festival (i.e. the Chinese New Year) in winter. During these celebrations, incense and fireworks are abundantly used in historic buildings, which leads to the occurrence of a significant number of fires. Furthermore, the drier weather conditions usually found in spring and winter also facilitates fire ignition to occur in wooden historic buildings [17]. In addition, given the cold weather conditions in these two seasons, the more intense use of heating equipment and electricity also increase the likelihood of fires in historic buildings due to electrical malfunctions. The fire statistics also indicate that autumn is the season with the fewest fires in historic building. The main reasons for this are inferred to be the fact that autumn is more humid than winter, that religious festivals are rare during this season, and that heating and other electrical equipment are not used as frequently in autumn.

2.1.3. Fire causes

The relation between the number of fires and their causes between 2000 and 2017 are illustrated in Fig. 2. The causes are divided into fire related to electrical factors (e.g. malfunctions, short-circuits, arc faults, etc.), human factors (e.g. arson, construction works, smoking, playing with fire, careless use of fire such as when cooking, handling fireworks or incense, etc.), and natural factors (thunder, and spontaneous combustion caused by dry and high-temperature conditions). It can be seen that the various types of fires have peaks in certain years. When the number of fires increases abnormally in a certain year, the number of fires will decrease in the following years due to an increase in the people's awareness and prevention practices. This phenomenon agrees with the bathtub curve of human reliability [18]. As referred before, the dry weather can increase the fire risk in historic buildings [17], which agrees with the fact that fires caused by human factors increased sharply. Also, it is found that the number of fires from 2012 to 2017 is higher than the average number of 39. Although the number of fires caused by human factors has decreased to the critical value concerning the fitting linear after 2012 [19], the number of electrical fires still increased, which resulted in a higher number of fires than in previous years. To further detail the causes of past fires in historic buildings, the data associated with each family of factors is discussed in the following.

Fig. 3 describes the proportion of fires caused by different reasons from 2000 to 2017. It indicates that fire causes in historic buildings could be divided into electrical factors, human factors, and natural factors. Human factors include arson, construction work, careless use of fire (such as cooking, fireworks, and incense fires), smoke, and playing with fire. Natural factors are summarized as spontaneous combustion (non-manmade fire caused by dry and high-temperature conditions) and thunder. The factors are detailed in the following, respectively.

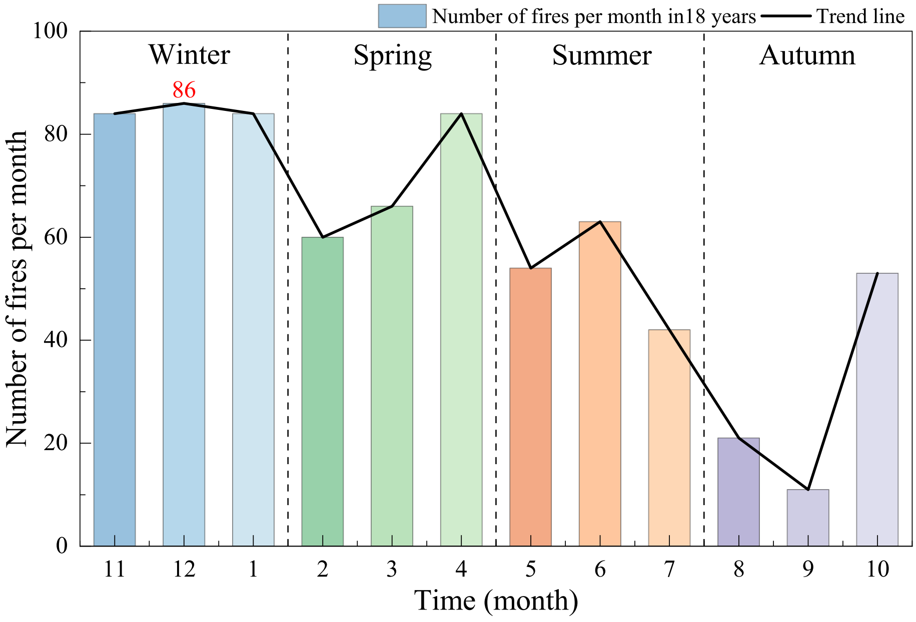


Fig. 1. Number of fires in historic buildings across the months between 2000 and 2017.

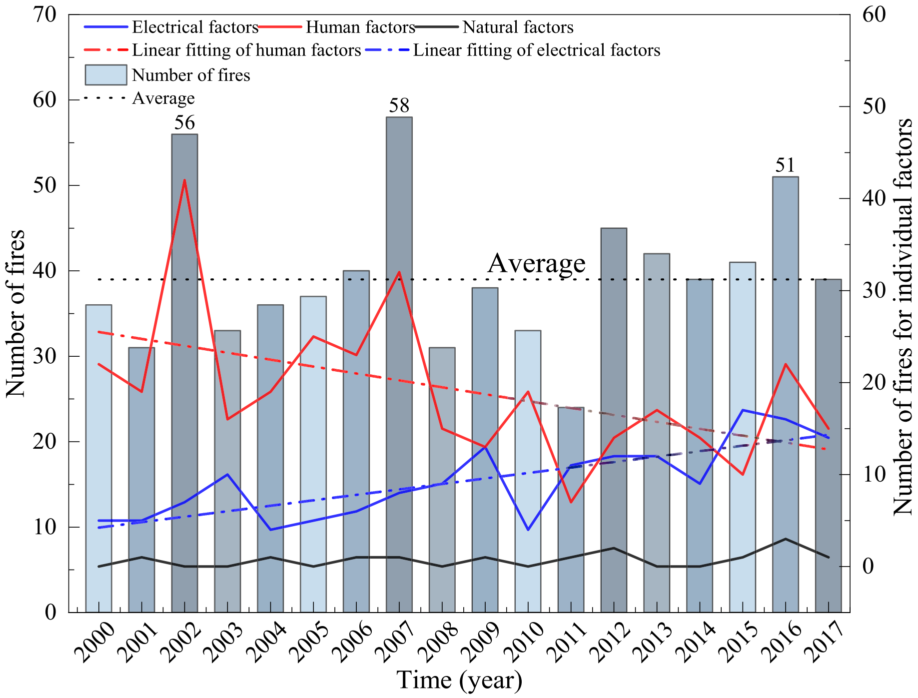


Fig. 2. The number of fire numbers varying years and fire causes regarding historic building fires in 2000–2017.

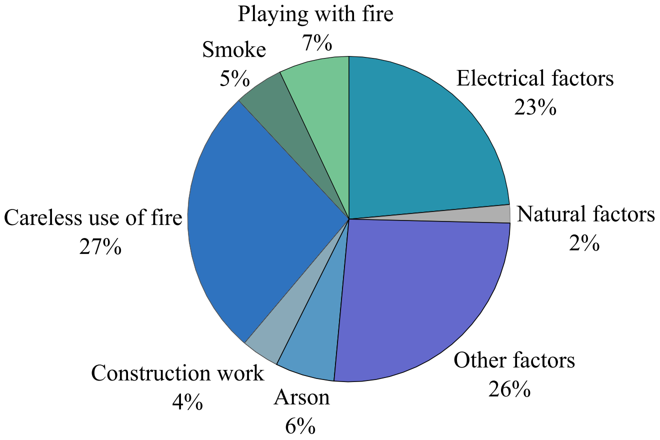


Fig. 3. Disaggregated proportion of fires caused by different factors between 2000 and 2017.

(1) Electrical factors

From the available statistical data, 23 % of historic building fires were caused by electrical factors (Fig. 3). With the enhancement of China's economic and technological strength, the degree of electrification has increased, and the utilization rate of electrical equipment in various levels of society is seen to be much larger. As such, it can be inferred that fires caused by electrical factors are related to the development of China. Up to now, there are still various non-standard methods for the use and installation of electrical equipment. Some of them have already caused fires in historic buildings, resulting in an overall upward trend of electrical fires. Globally, electrical factors are believed to be the most common cause of historic building fires.

(2) Human factors

According to Fig. 3, nearly half of historic building fires are caused by human factors. Due to the frequent use of fire in people's lives, careless use of fire has become one of the most dominant human factors. Still, other human factors, such as playing with fire, arson, smoking, and construction work cannot be ignored. However, due to the people's constant attention to safety, they account for 4 % to 7 % of the fires, which is relatively low. So far, the people's awareness to the importance of fire prevention has also improved significantly as the result of China's investments in education [20]. Therefore, the number of fires in historic building caused by human factors is exhibiting a downward trend in recent years.

(3) Natural factors

Sometimes, fires in historic buildings can also occur due to natural factors (Fig. 3). Based on the available data, the number of fires caused by natural factors appears to be relatively stable. Among those, lightning strikes are seen as one of the main causes of damage to older buildings, and is attracting a great deal of attention [21]. This can be explained by the fact that the conditions for the occurrence of fires due to natural factors are coincidental.

2.1.4. *Fire damage*

The relation between the direct losses caused by the fires in historic buildings and the number of fires is shown in Fig. 4, while the relation between the burned-out area and the number of fires is shown in Fig. 5. Direct losses include the direct property loss, the fire scene disposal cost, and the personal injury and death fee, which can be directly calculated by the actual cost amount. The cultural and heritage values are not mentioned because they are incalculable. From 2000 to 2017, the maximum direct losses were 11.76 million RMB in 2013 and the maximum burned-out area was 5930 m^2 in 2004. According to the previous statistics, the number of fires did not show an abnormal increase in those two years. However, when both direct losses and burned-out areas were relatively low (e.g. in 2002), the number of fires caused by human factors increased abnormally. In the correlation analysis between fire causes and damage, no clear relation is found between them. To further explore the bond between these two elements, a quantitative analysis method should be used to calculate the relation between fire damage and different fire causes, which would be useful for managing

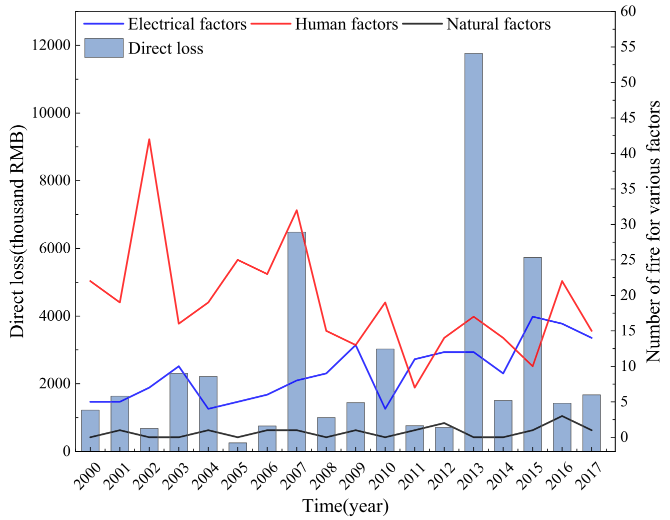


Fig. 4. Direct losses and trend of fires caused by various factors between 2000 and 2017.

fire protection.

2.2. *Analysis of fire factors*

The seriousness of fires in historic buildings and the need to clarify the corresponding causes were discussed in the previous section. However, the relation between the different causes and the level of fire damage is difficult to determine using QSA. Therefore, the GRA method is introduced herein to objectively examine the relational degree of direct losses versus fire causes, and of burned-out area versus fire causes, by quantifying the insignificant correlations between the sequences. The primary fire cause with the greatest impact on direct losses or burned-out areas can be determined.

2.2.1. *Grey relational analysis*

The data on direct losses and burned areas available in the fire protection yearbooks of China are summarized in Tables 1 and 2 in the Appendix. The fire damage in historic buildings was divided in two categories, corresponding to the direct fire losses and burned areas in Table 1. The causes of fire damage were divided in 8 types which correspond to those described in Table 2. With respect to the origin of fires, they correspond to arson, electrical factors, construction works, careless use of fire, smoking, playing with fire, spontaneous combustion, and lightnings. For example, electrical factors include short circuits and damaged electrical equipment. Construction works accounts for different types of legal or illegal operation that generates a source of ignition or involves hot works. Careless use of fire varies from incense burning, fireworks, and the use of fire in cooking or other kitchen activities.

Here, the direct losses and burned area are chosen as the reference series, and the 8 causes of historic building fires are used as the comparison series. Then the relational degree between direct losses versus and causes, and between burned areas and fire causes is calculated, respectively. The results are shown in Figs. 1 and 2 of the Appendix. As shown, the relational degree between direct losses and fire causes is ranked as electrical factors (0.81) > arson (0.80) > careless use of fire (0.79) = playing with fire (0.79) > smoking (0.78) > construction works (0.76) > spontaneous combustion (0.72) > lightnings (0.70). Meanwhile, the relational degree between burned areas and fire causes is the following: electrical factors (0.85) > careless use of fire (0.84) > arson (0.82) = smoking (0.82) > playing with fire (0.81) > construction works (0.79) > spontaneous combustion (0.70) > lightnings (0.68).

Although certain factors have the same relational degree, by comparing the results between direct losses and burned areas, it is possible to identify three factors that have significant impacts on both fire damage categories. These three important factors are electrical factors, careless use of fire, and arson. From the results of QSA, electrical factors and careless use of fire account for a large proportion of fires in historic buildings. However, the number of fires due to arson is far less than those related to electrical factors and careless use of fire. Therefore, it seems difficult to reduce the severity of arson at present. For this type

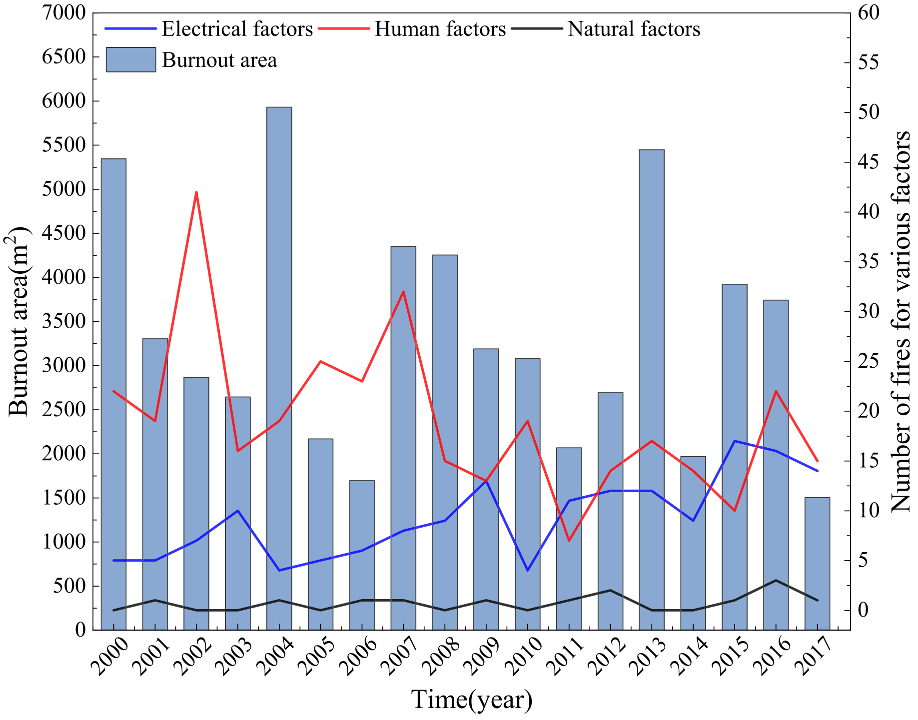


Fig. 5. Burned-out area and trend of fires caused by various factors between 2000 and 2017.

of source of fire, it is hard to discuss the seriousness of the fire damage based only on the number of fires. For the merits of the GRA method, even if the correlation between sequences is not obvious, the importance could be easily determined by quantitatively comparing it with the relational degree. A comparison of the results indicates that the number of fires does not agree with the severity of the damage in historic buildings. In some cases, the impact of a certain factor on fire damage is large but the number of fires caused by that factor is small.

2.2.2. *Fire causes*

Based on the analysis results of the GRA, the causes of fire were divided into three levels: primary causes, secondary causes, and general causes. Primary causes include electrical factors, careless use of fire, and arson. Secondary causes consist of smoking, playing with fire, and construction works. General causes involve spontaneous combustion and lightnings. A more detailed discussion of the primary causes in presented in the following.

(1) Electrical factors

According to the results of the QSA and GRA, it can be seen that electrical factors are an important cause of fires in historic buildings. In the QSA, fires caused by electrical factors account for a large proportion of the total number of fires. Furthermore, the number of fires related with electrical factors exhibit an upward tendency due to the commercialization of historic buildings in China [22]. In the GRA analysis of fire damage, the relational degree of electrical factors is greater than for other causes. From this analysis, this factor is the primary cause of fires in historic buildings and, since the number of electric fires is large, the overall damage is also significant. Furthermore, the damage to historic buildings caused by fires starting from electric factors shows an upward trend over the years. As such, it is necessary to improve prevention measures for this type of fires. It is known that electrical factors comprise damaged electrical equipment and short circuits. Regarding the damaged electrical equipment, it usually involves overheating of high-power equipment during a long-term operation which ignites the surrounding combustible materials. Fires in historic buildings due to short circuits are caused by damage to the surface coating of electrical wiring. In China, due to the inadequate protection policy for cultural relics, many historic buildings are used for other purposes and managed loosely. In such cases, the installation of electrical equipment is found to involve non-standard procedures, leaving a large area of electrical wiring installed directly on the surface of the building without any fire protection measures, which greatly increases the risk of fire in historic buildings.

(2) Careless use of fire

Careless use of fire is also an important cause of fire damage in historic buildings. According to the result of the QSA, careless use of fire is the most common cause of fires in historic buildings, but shows a downward trend due to the improvement of educational levels. When analyzing the GRA results concerning the direct losses and burned areas, the relational degree of fire carelessness is found to be less than that of electrical factors, but greater than that of other causes except for arson. Despite the reduction in the number of fires in historic buildings caused by careless use of fire in recent years, it still accounts for a large part of the total amount of fires and ranks at the top when analysing the relational degree. Therefore, it is concluded that the careless use of fire is the primary cause of fire damage in historic buildings. According to the research, there are three types of careless use of fire: kitchen fires, fireworks, and incense burning. A kitchen fire involves the accidental ignition of combustibles during cooking, whereas fireworks consider sparks that ignite combustibles. Incense burning leads to a fire because of the incomplete extinguishing of the fire source. It is important to note that the wood structure of historic buildings is more easily ignited than that of other buildings. In light of these findings, adequate attention should be given to fire control management in daily life to avoid fires caused by the careless use of fire.

(3) Arson

The number fires in historic buildings due to arson is small. However, it is an important factor in terms of losses to historic buildings. In the QSA, fires caused by arson account for a small proportion of the total number of fire and it is difficult to conclude that arson is the primary cause of damage to historic buildings. In contrast, the GRA of direct losses versus fire causes indicates that the relational degree of arson is 0.80. The GRA of burned areas versus fire causes shows that the relational degree of arson is 0.82. When comparing the results of QSA and GRA, it can be seen that the number of fires is not in a positive proportion to the fire damage. The main fire causes cannot be determined based on the results of QSA. With the help of GRA, the main fire causes that have a large impact on direct losses and burned area were calculated and ranked, providing an important reference to fire protection management regarding historic buildings. In addition, even though the number of fires caused by arson is relatively small, the losses and the burned areas caused by arson are often much larger than those caused by other types of fire. Therefore, arson should be considered as a significant cause of fires in historic building given its impacts.

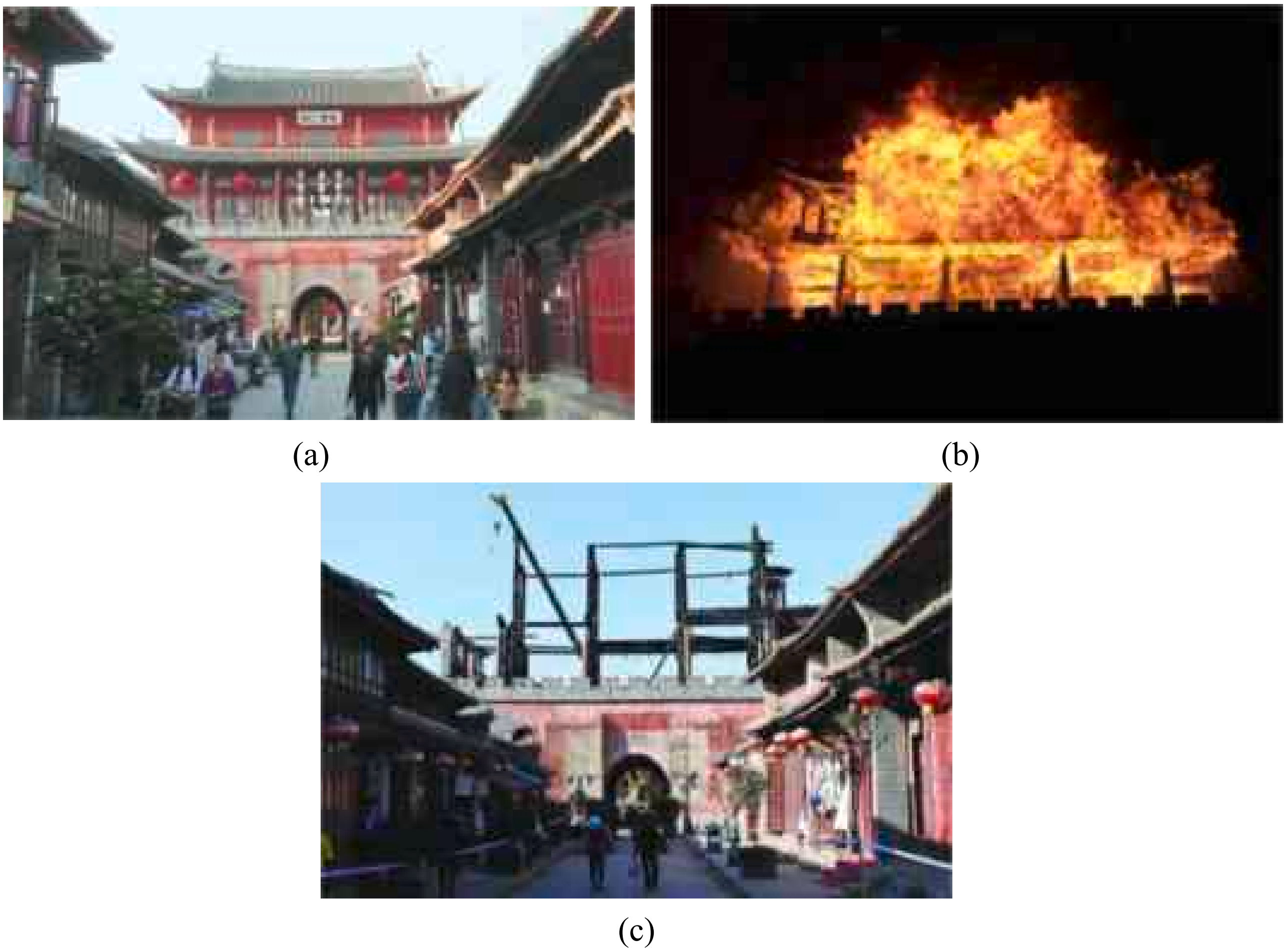
According to the presented discussion, the primary causes of fires in Chinese historic buildings are found to be electrical factors, careless use of fire, and arson. The different lifestyles and culture types would exhibit varying historic building fires. The typical cases of fires in historic buildings caused by these three factors are illustrated in the next section, hoping to provide reference and lessons for developing adequate fire protection measures in historic buildings across the world.

2.3. *Introduction of typical historic building fire cases*

To show the damage of historical building fires caused by primary causes, the following typical fire cases are given to illustrate.

2.3.1. *Gong Chen Lou fire (built-in 1648)*

The Gong Chen Lou is located in Wei shan Ancient City, Yunnan Province. It was built in 1390 and rebuilt as a two-story building in 1648. It belongs to the National Key Cultural Relics Protected Unit (i.e. a site protected at the national level). In January 2014, during an inspection, the fire department found that the ceiling of the hall, which is the exhibition site of Nanzhao ancient music, was decorated with cloth made of flammable materials. At the same time, multiple electrical wiring was directly laid over wooden components above those decorations and was considered a major fire hazard. The fire department put forward suggestions to correct these issues in order to improve the fire safety level of Gong Chen Lou, but the problem still existed during a new round of inspections that month, even before the fire broke out. On January 3, 2015, the Gong Chen Lou was severely damaged by a fire. After the fire department received an alarm at 2:49 on January 3, 2015, all fire trucks were at the location at 2:55. There are 6 fire hydrants around the tower, 5 of which were used that night, and the water supply was not cut off. However, as Gong Chen Lou is a wooden structure, the surrounding area was empty, and the air circulation was large. Therefore, flashover occurred in the middle area, and the flames quickly rushed to the top of the building. The area of the fire was about 300 m^2, but there were no casualties. Still, the main body of Gong Chen Lou City Gate was burned (see Fig. 6). The fire started at the southeast corner of the building. The fire in the city gate was caused by an electrical short circuit, which is one of the previously highlighted electrical factors. The sparks ignited the combustibles and caused the spread and expansion of the fire.



(a) (b) (c)

Fig. 6. Fire damage to Gong Chen Lou (a) prior to fire (b) in the fire (c) after the fire (https://www.sohu.com/a/15313209_110565).

2.3.2. Du Ke Zong ancient city fire (built-in 719)

Du Ke Zong ancient city has a history of more than 1300 years. Located in Yunnan Province, it is the best-preserved and the largest Tibetan residential community in China. Most of the buildings in the ancient city are in timber. At about 1:10 on January 11, 2014, a fire broke out in the Du Ke Zong ancient city. The total area of housing that was burned by the fire was 599.8 million m^2 (which includes an area of 58.121 m^2 of houses that burnt down and an area of 1859 m^2 of houses demolished during the fire fighting and rescue process). The area of the damaged cultural relics is 2220.45 m^2, which accounts for 3.7 % of the damaged built area. The ancient city with a history of more than 1300 years was almost destroyed, and the economic loss reached 89.839 million RMB (excluding other direct property losses and public facility losses such as decoration, house facilities, equipment, items, etc.).

The fire accident was the direct result of a person improperly using a five-sided halogen heater in the bedroom. As the person did not turn it off the power before going to bed, the heater accidentally ignited combustible materials and caused a fire. This example belongs to the careless use of fire in the previously highlighted human factors.

An indirect cause for the large size of the fire was that 68 % of the hydrant drains were blocked due to the modification of the buttresses. Four fire hydrants opened by firefighters while fighting a fire. However, the hydrostatic water in the pipe section was frozen due to long-term heat exchange from the permafrost, making it difficult to drain the fire hydrant control valve when it was opened. Furthermore, the water provided by fire trucks could not meet the fire demands, causing the fire to spread. Moreover, it was found that the specific anti-freezing measures for fire hydrants did not strictly follow the national engineering construction fire protection technical standards. The pipelines were not buried in strict accordance with the design requirements, and the depth of soil on the top of some fire hydrant pipes did not meet the requirements, leaving it unable for the fire hydrants to defect the low-temperature freezing congenital in plateau areas. In addition, due to the long and deep tunnels that exist in the ancient city of Du Ke Zong, large firefighting vehicles could not enter or pass through. The fact that buildings in the ancient city were mostly made of wood with low fire resistance also contributed to the size of the fire. Furthermore, a large number of bars, inns, restaurants and other businesses used diesel, liquefied petroleum gas, or other flammable and explosive materials. Insufficient pressure in the municipal firefighting water supply network and failure to coordinate in time to provide pressure protection when fighting fires are also indirect causes of the accident.

2.3.3. Falun Temple fire (built-in 1745)

The Falun Temple is a National Key Cultural Relic Protected Unit and it is located in Chifeng City, Inner Mongolia. It was built in 1745 and was well-preserved. The east side hall of Falun Temple was destroyed by a lightning in 1937 and was rebuilt between 1939 and 1941. It has an area of about 50 m^2 and it is a civil-wood double-storey structure.

On October 30, 2017, a fire broke out at the Dong Pai Hall of Falun Temple, which caused the main (Fig. 7) body of Dong Pai Hall to be burned down, leaving only one wall standing (see Fig. 8). After a preliminary investigation, the cause of the fire was found to be related to the fact that the staff of the Falun Temple put a recently extinguished oil wick in a cardboard box in the east hall before getting off work and leaving. After 9 min, the oil wick reignited and caused a fire. This is also a fire caused by human factors or personnel's poor management of fire

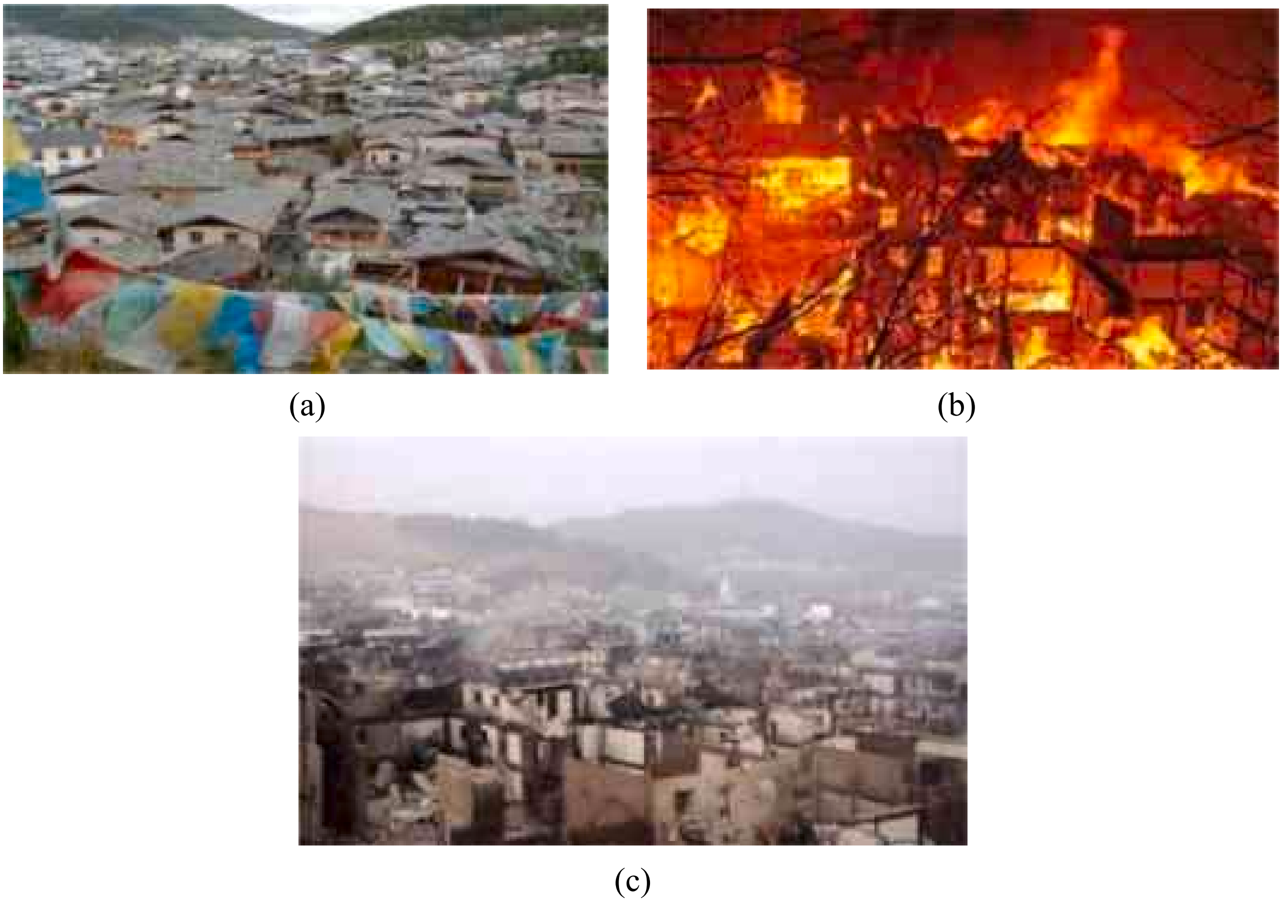

(a) (b) (c)

Fig. 7. Fire to Du Ke Zong ancient city. (a) prior to fire (b) in the fire (c) after the fire (http://www.chinadaily.com.cn/dfpd/2014-01/14/content_17233888_4.htm).


(a) (b)

Fig. 8. Fire to Falun Temple (a) prior to fire (b) after the fire (http://www.chinanews.com/cul/2017/11-01/8365807.shtml).

sources. The fire caused the 50 m^2 Dong Pai Hall to be burned to the ground, but there were no casualties.

2.3.4. *Zheng Ding ancient city gate fire (built-in 1619)*

The Zhengding City Gate, located in the Zhengding City of the Hebei Province, is one of the four city gates of Zhengding City, which has a history of more than 400 years. The City The gate is a double-layered wooden structure with a brick rampart at the bottom. The south of the gate is a two-story loft-style building with a wooden structure, which is relatively flammable. There are fire hydrants on the south and north sides of the city gate, and fire extinguishers are placed in the attic also.

The fire at the Zhengding Ancient city gate occurred on February 18, 2010, and started at the cornice of the top floor of the pavilion. After the fire broke out, the Zhengding fire department immediately mobilized to put out the fire with all its strength, and the Shijiazhuang fire department also rushed to provide support. At a certain point, there were seven fire engines gathered at the scene. Due to the elevated location of the fire, and wind conditions at that time, the fire spreads quickly through the wooden structure. The fire was extinguished after it burned for two and a half hours. At that, the two-story pavilion above the gate was completely in ashes. The area hit by the fire is about 400 m^2 and it burnt the upper two layers of the wooden structure, leaving only the bottom brick rampart (see Fig. 9). The fire did not cause any casualty. The fire was caused by the sparks of fireworks, which ignited the wooden structure of the city gate. Although two staff members on duty found the fire on the east side of the loft in time that night, and quickly called the fire department and used fire extinguishers to fight the fire, the fire spread rapidly and uncontrolled, particularly due to the wind conditions.

3. Research progress on the fire protection of historic buildings

Although historic building fires occur frequently and are relatively serious, research connected to the prevention and control of fires has been advancing. Therefore, some of the research progresses achieved in fields related to historic buildings and fire are discussed in the following, focusing on aspects connected to fire detection and early warning, firefighting, and post-disaster restoration in particular.

3.1. *Fire detection and early warning*

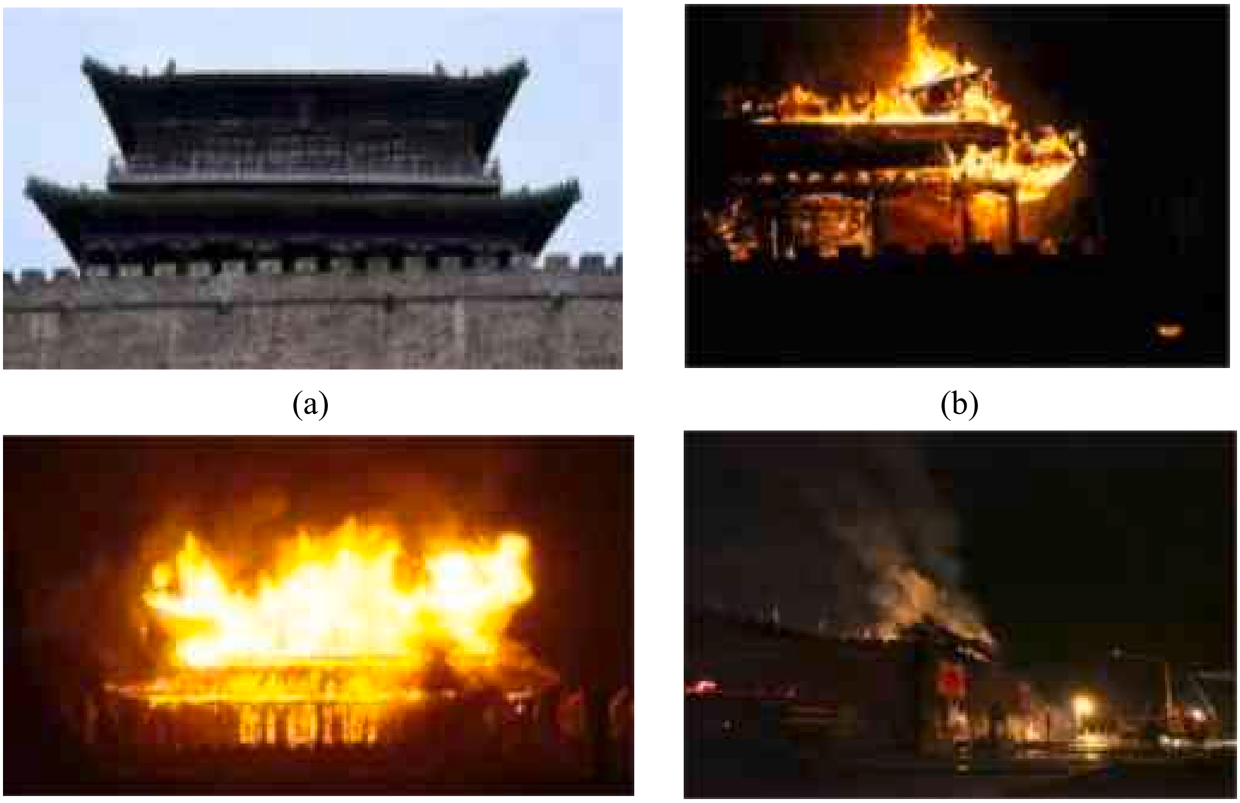
Limited by the fact that the ancient building is an open space as a whole, the floor height exceeds the scope of conventional public buildings, and the interior of the building is long-term affected by incense burning and people flow, the fire detection and early warning system often has unreasonable design, which leads to a false alarm and late reports. To better adapt to the special environment of ancient buildings, the applied technology of the system should also meet the following requirements [23]: a suitable fire response temperature and the shortest response time, maintaining the stability of itself and the monitoring signal for a long time, and high adaptability and easy operation.

During the past several years, various fire warning materials and probing technology were explored to meet the needs mentioned above. As shown in Fig. 10 (a), key achievements have been made in the smart fire alarm system (FAS) in recent years.

(1) Resistance transition monitoring

Regarding resistance transition monitoring technology, fire detection and early warning signals can be triggered by the resistance transition caused by temperature changes [28]. The materials applied to this technology have characteristics of electrical insulation and flame retardancy under normal conditions. The operating principle is that in case of abnormal temperature change caused by flame, cigarette, etc., the resistance value of the materials will change dramatically and even convert from the electrical insulation state to the sensitive state of high conductivity state [23]. Therefore, an early warning response can be activated by changing the current flowing through the conductive network before the combustible generates an open fire. Compared with the disadvantages of long response time of traditional detectors and the impact of corrosive environment and radiation, this technology depends on various nanomaterials based on the principle of temperature-sensitive resistance conversion. The materials with temperature change sensitivity and self-stability include MXene, graphene oxide (GO), Carbon Nanotube (CNT), etc. The techniques used for smart early-stage fire warning (EFWS) from the perspective of mechanisms and performances is summarized in Fig. 10 (c).

Among them, MXene is the most rapidly developed material [29]. As a synergist, the novel intumescent fire-retardant coating (TFIFC) developed with MXene has significantly improved its thermal stability and flame-retardant performance, which fully verified the application possibility of MXene material in fire detection of historic buildings [30]. As a sensor network, MXene is embedded in the multi-functional coating



(a) (b)

(c) (d)

Fig. 9. Fire at the Zheng Ding ancient city gate. (a) prior to fire (b) and (c) during the fire (d) after the fire (https://www.sohu.com/a/295493834_120059653).

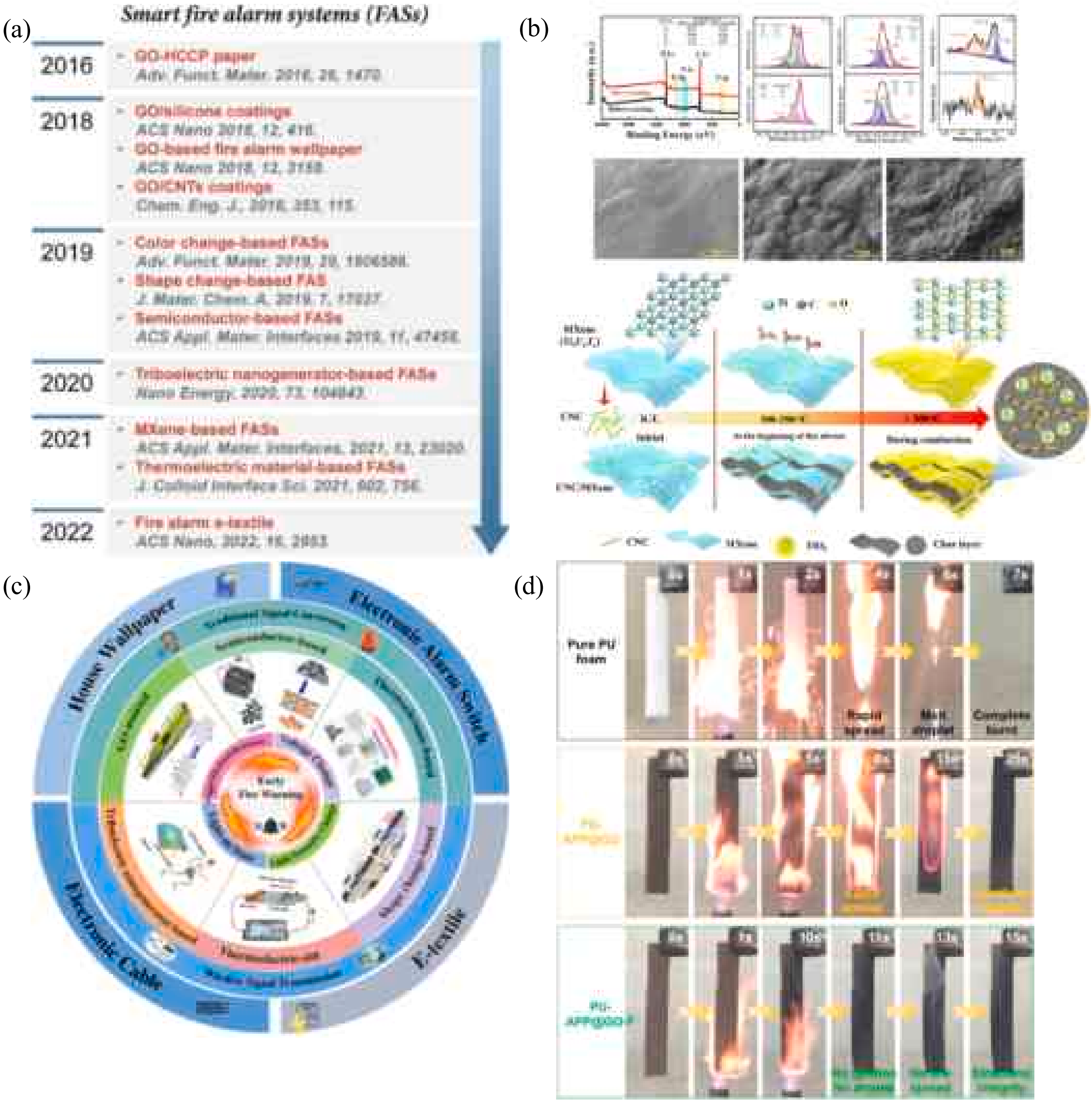


Fig. 10. (a) Chronology of key achievements made in the smart Fire Alarm Systems (FASs). [24] (b) Fire warning mechanism [25] (c) Summary of the mechanisms and performances of smart Early Fire Warning Sensors (EFWSs) [26] (d) Comparison of vertical burning testing processes of pure PU foam, PU-APP@GO, and PU-APP@GO-F. [27].

of wood to realize the warning function, and the mechanism of the multi-functional coating is shown in Fig. 10 (b). During combustion, MXene-based coating not only facilitates electronic transmission under temperature changes, but also prevents smoke escaping by extending the physical barrier [25]. For the weathering test of wood surface, the coating network can still maintain superhydrophobicity and flame retardancy with the fire warning and recovery times of ~ 1.8 s and ~ 1 s after silanization treatment and one-year outdoor exposure [29]. In view of the reusability challenge in the application process, the coating network can be prepared in a simpler and environmentally friendly way to be adapted to the large area of wood surface. Although MXene has excellent flame retardancy, smoke suppression, signal transmission and weathering resistance, it needs to be pre-hydrophobic because it is prone to oxidation in environment.

Besides, breakthroughs have been made in the research of Graphene Oxide (GO) in detection and early warning. On the one hand, the hybrid layer composed of GO, ammonium polyphosphate (APP) and silane can provide more efficient fire alarm while synergistically flame retardant shown in Fig. 10 (d) [27]. The conductive reduced graphene oxide paper (RGOP) prepared by auxiliary GO has flame-triggered self-cutting performance, which can block the spread of flame in time [31]. On the other hand, a multifunctional fire alarm film can be prepared in form of coupling GO with MXene. This film not only has highly sensitive fire warning capability at low temperatures due to MXene, but also combines the signal transmission conversion characteristics of GO, greatly reducing the fire response time to 1 s. Under the condition of introducing a photometric sensor, the fire alarm signal is transmitted wirelessly [31]. In terms of response time, the most prominent result is that the hybrid network of the water-soluble multi-amino molecule (HCPA) and GO can shorten fire response time to 0.6 s [32]. In terms of detection range, in order to break through the limitation of the concentrated detection range of most GO-based sensors, a large-scale sensor was developed which can respond to fire phenomena within 3 s [33].

The above materials are mainly applied to timber substrate materials through coating technology. Among them, the treatment forms of coating processing include dip-, drop-, spray-, rod-, and brush-coating [24]. If taking the trigger temperature of the alarm signal into consideration, in the color change-based FAS, the trigger temperature of the device with polyhedral oligomeric silsesquioxane (POSS), Cr $(NO_3)_3 \cdot 9H_2O$ as the component is 80℃ [34], while the trigger temperature of the device with liquid metal microdroplets/ polyborosiloxane elastomer (LM/PBSE) as the component is 55℃ [35]. For the shape change-based FASs, the trigger temperature of devices consisting of PCL and Ag layer is 45℃ [36].

To sum up, in terms of transition resistance monitoring materials, MXene, GO, and other materials have made achievements in improving flame retardancy, shortening response time and reducing response temperature respectively. However, these materials generally have the problem that the coating area in the experimental and application stages is still small.

(2) Thermoelectric response

As a promising material, the thermoelectric material (TE), the core of thermoelectric monitoring, can convert the change and migration of temperature gradient into electrical signals [37]. The working principle of thermoelectric materials is to transform the received thermal energy into electrical signals and electrical energy, and finally, present it in the activated state of the alarm light switch [36]. In addition, the converted fire alarm electrical signal is also expected to achieve the goal of autonomous power supplement [38], avoiding the impact of frequent detector replacement on system operation.

The detection and early warning device based on thermoelectric effect is limited by the floor height, area and space openness of historic buildings, so its application in the field of ancient building fires is relatively limited. However, the energy conversion ability of thermoelectric materials can still respond quickly to fires caused by abnormal temperature rise, and independent power supply is also a major advantage worth looking forward to.

(3) Image Monitoring

As two characteristics of flame, color and radiation have two corresponding flame detection methods, namely visual technology and non-visual technology [39]. The basic idea of both technologies is to design a smart fire-warning system by extracting fire pixels and smoke pixels from flame radiation [23]. Compared with traditional smoke detectors or heat detectors, which require the smoke concentration or heat radiation to reach a critical value to trigger the alarm, the video fire monitoring system is more sensitive, accurate, intelligent, and anti-interference [40]. Depending on the flame temperature and fuel type, ultraviolet, visible, and infrared sensors are available for flame sensing and categorized based on their spectrum. When applying the flame color monitoring method, two types of cameras can be utilized for flame detection, namely infrared radiation (IR) and visible cameras. After obtaining the flame image through the camera, it is necessary to use algorithms to identify and process the image. Learning algorithms and neural network are the mainstream algorithm research directions at present. Although the research on both algorithms are still at the initial stage, it has been proved that the multi-sensor system using BP neural network can predict electrical fires in historic buildings with high accuracy through fire pyrolysis particles [41]. In terms of functional implementation, a smoke detection algorithm with 99 % detection accuracy can be developed by combining smoke features and convolutional neural networks (CNN) [42]. A detection method for multi-feature fusion of flames can also be developed through the flame centroid stabilization algorithm based on spatiotemporal relationship, which realizes the dynamic real-time monitoring [40]. In terms of monitoring parameters, the backpropagation neural network (BP) usually selects temperature, smoke and CO concentration parameters as comprehensive analysis objects to further judge the fire probability. Through 12 scenarios and 6 sets of standard experiments, it is proved that this method can shorten the fire detection time by 32 % [43].

As the most direct fire detection and early warning method, image monitoring can monitor whether dynamic open flames are generated in real time. Although this technology will be strongly interfered by factors such as burning incense and thick smoke in the process of pixel extraction, the problem of interference can be basically solved by screening the recognition processing of different algorithms. The functions of intelligent recognition and real-time dynamic monitoring that are more suitable for historic building fires are also expanded.

(4) Networking

It is widely known that the networking methods of sensors can be divided into wired and wireless. Since the traditional electrical fire monitoring system has the hazards of maintenance, aging, and short circuit of wired network transmission wiring, the research on the networking of ancient buildings is based on wireless mode. Because of the above contents, the electrical factor is the main cause of the fire, the wireless sensor network with JN5148 wireless low-power embedded processor as the core and with JenNet protocol as the basic frame architecture provides intelligent communication means from terminal to midrange for the fire alarm system [44]. Moreover, according to the higher demand of cloud computing for computing load and bandwidth pressure, an electrical fire monitoring and early warning Internet of Things (EFM-IoT) framework was developed to optimize algorithm scheduling [45]. Due to the ultra-low response latency, large-scale deployment, and dynamic updates of, EFM-IoT can reduce the average end-to-end delay and task waiting time by real-time monitoring the residual current in the electrical appliances. Therefore, wireless networking technology can not only fundamentally eliminate fire hazards caused by electrical factor, but also visualize the monitoring system with the advantages of determining the fire location and shortening long-distance transmission time. However, the problems of insufficient computing power, signal interference and space layout still need to be solved.

In general, based on the three mainstream methods of transition resistance monitoring, thermal resistance monitoring, and image monitoring, and assisted by a new networking mode, fire monitoring and early warning have been able to achieve intelligence and visualization. Some new monitoring and early warning materials have good flame retardant and conductivity, which are ideal application materials, and are expected to be used in the field of historic buildings as soon as possible.

3.2. *Fire extinguishing methods*

As a timely rescue measure, this part introduces the research progress of fire extinguishing technology mainly represented by water mist extinguishing and gas extinguishing technology to maximize the protection of buildings. The impact of fire-fighting on the surrounding environment is also described.

3.2.1. *Water mist*

Compared with the traditional spray system, the water mist system provides a wooden building fire suppression by the method of evaporative cooling [46] and oxygen displacement [47] through three stages of cooling, inerting, separation, and shielding effect [48] using less water [49] and finer droplets. According to the composition of the system, including nozzles, atomizing medium, the piping system, and water supply equipment [48], recent research mainly focuses on the aspects of extinguishing media, trigger conditions, and jet type.

In terms of extinguishing media, based on the wood crib fire experiments, the new generation of MC additive, 2-bromopropane-3,3,3-trifluoropropene (BTP) and potassium salt solution have been proved to be effective in suppressing wood fire. Among them, by further clarifying the improvement degree of MC additives on the system extinguishing efficiency, the optimal content of MC additives which made up of $(C_2F_5)_2(CF_3)C(CF_3)C{=}C(CF_3)\text{-}OC_6H_4SO_3Na$, $C_8H_{17}C_6H_4O(CH_2CH_2O)_{10}H$, CH_3COONa, carbamide and *N*, *N*-dimethylformamide is 0.8 wt%, as shown in Fig. 11. (a) [50], and a new portable water mist extinguisher has also been developed. Through the wood crib fire experiment, it turned out that the fire extinguisher can not only improve the fire-extinguishing efficiency but also is a potential fire protection means for historical buildings [51]. For BTP shown in Fig. 11. (b), the combination with water mist can effectively extinguish the wood crib fire by the mechanism of surface cooling and combustion inhibition. And in the process of suppressing the fire, the concentration of hydrogen fluoride (HF) acid gas released is within an acceptable range [52]. For potassium salt solutions, the active substance KOH released during the flame chemical reaction can participate in the reaction with free radicals in flames to produce extinguishing active substances. Through experiments, it is found that the order of potassium-containing salts for synergistic and fire extinguishing cooperating with pure water is $K_2CO_3 > K_2C_2O_4 > CH_3COOK > KNO_3 > KCl > KH_2PO_4$. According to the minimum and the maximum extinguishing concentration (MEC) shown in Fig. 11. (c), when the mass fraction of K_2CO_3 is 1 %, 2 %, and 5 %, the improvement rate of extinguishing efficiency is 37.6 %, 47.2 %, and 64.8 % respectively [53].

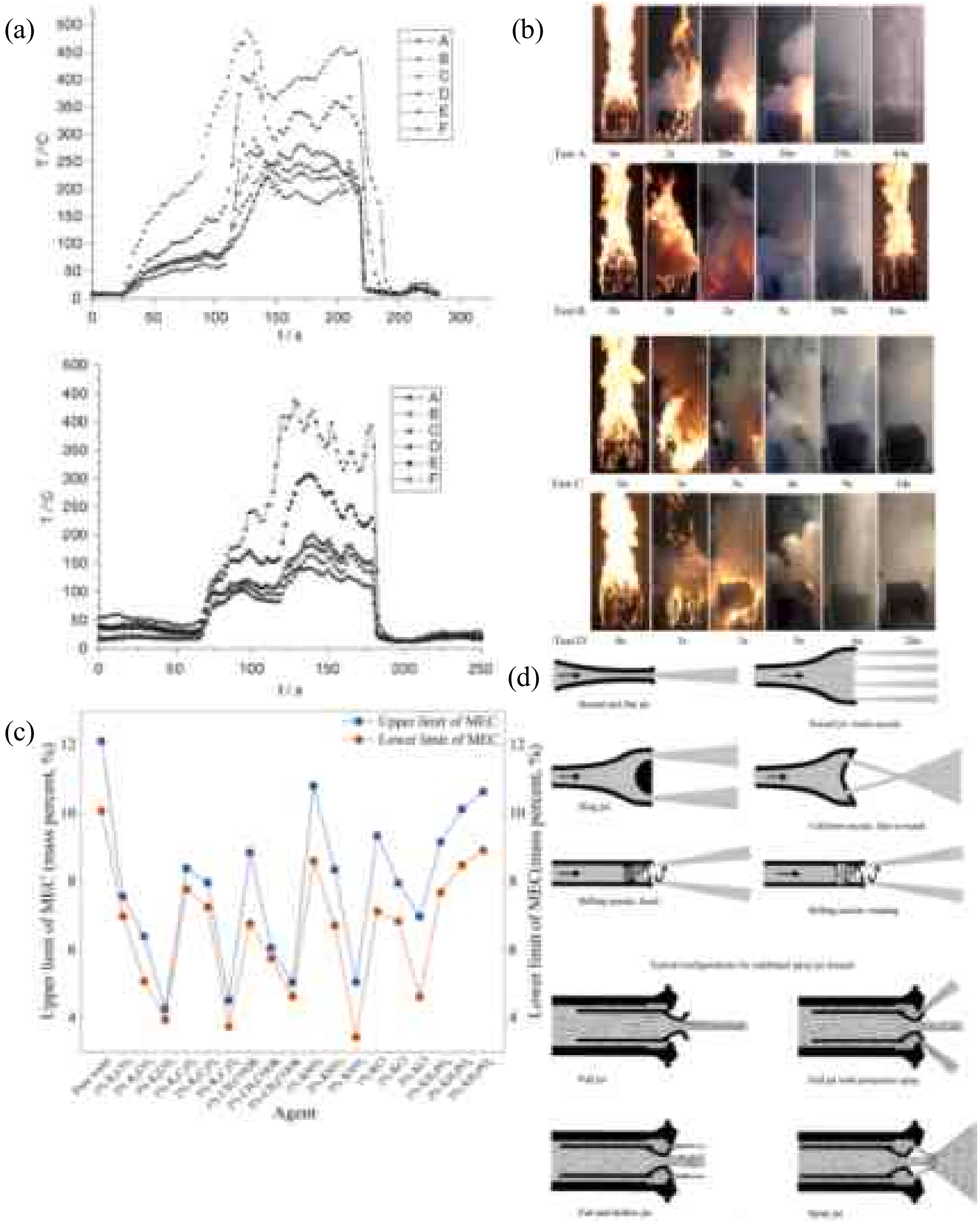


Fig. 11. (a) The relationship between additive (wt %) and extinguishing time (wood cribs), temperature and time without MC additive, temperature and time with 0.8 wt% MC additive [50]. (b) Typical timed testing photographs with water mist (WM) alone, BTP, BTP and then WM, BTP and WM simultaneously [52]. (c) The minimum extinguishing concentration (MEC) of water mist with potassium salt additives . (d) Schematic illustration of fire-fighting nozzles reproduced from [53][54].

Differing from the efforts on the composition of water mist, in respect of the trigger mechanism, there have been various attempts shown that the minimum average time to extinguish wood crib fire employing the nitrogen-driven water mist hybrid system is 205 s, in which the water flow rate is 3 dm^3/min. Compared with the air-driven type, the nitrogen-driven system extinguishes the fire in about 20 s and has a lower oxygen concentration of about 13 % when it extinguishes the fire with the method of displacing oxygen [55]. With the renewal of water-mist system equipment, studies have been carried out on wood crib fire experiments, using water with a foaming agent and nozzle-aspirated foam, and compressed air foam as the media, respectively, in combination with fire extinguishing media and jet-type which shown in Fig. 11. (d). Surprisingly, as the results shown, it is more effective to use water and water with foaming agents to extinguish long-distance fires in the form of a full jet rather than a spraying jet [56]. In addition, in terms of jet type alone, to accelerate and promote the guideline on creating automated fire prevention systems in buildings, a fire model experiment using a series of Class A combustibles, including wood, concluded that the discharge density required for wood fire extinguishing was 8.7. The discharge density meets the requirements of water discharge density and the minimum spraying time, calculated by multiplying the specific discharge density of the FMT-100 nozzle ($\psi \approx 0.03$ L/(m^2·s)) by the spraying time (time of fire suppression) [57].

In summary, based on wood crib fire experiments, the latest scientific research achievements, including extinguishing media, trigger mechanism, and jet type, are approaching the environmental parameters of actual historic building fires. In view of the problems of open space reburning and wood deep combustion, while the existing research pay more attention to the effective cooling and atomization of fire extinguishing media, the covering capacity of wood surface and the submergence characteristics of the environment. By optimizing the concentration of effective fire extinguishing medium, the water mist released method driven by inert gas, and adjusting the jet mode and spraying range, it is ensured that the water mist can suppress and extinguish the fire source by means of evaporative cooling and oxygen replacement. Among them, in terms of fire extinguishing medium, MC additive has the lowest optimal concentration and the highest extinguishing efficiency. The second is potassium salt additives, which are widely used because they are more readily available in daily industrial production. For brominated organics, attention should be paid to the amount of corrosive gases such as hydrogen fluoride generated during firefighting. In terms of trigger mechanism, using inert gas such as nitrogen as the driving gas can assist the water mist to reduce the oxygen content in the fire area, but it also weakens the safety of personnel search and rescue. In terms of jet types, not all historic buildings are suitable for spray jets, and factors such as extinguishing media and equipment installation should also be considered.

3.2.2. *Gases*

Since the implementation of the Montreal Protocols in 1987, the ozone-depleting chemical, halons, has been subject to a mandatory phase-out ban on production and application. The search for a new generation of halon alternatives has become a research hotspot worldwide. In recent years, significant progress has also been made in the mainstream research directions of new haloalkane gas and aerosols. Depending on the content of fluorine, chlorine, and bromine in the compounds, halon extinguishers exhibit different fire extinguishing effectiveness, chemical, and thermal stability, toxicity, and volatility. For example, fluorine can enhance the stability and thermal stability of compounds, and reduce their toxicity and boiling point. On the other hand, Chlorine plays a role in enhancing the toxicity and fire-extinguishing ability of compounds, increasing their boiling point and weakening their thermal stability [58].

To cope with the problem of environmental destruction of the ozone layer by gas fire extinguishing agents, new fire extinguishing agents such as perfluoro-2-methyl-3-pentanone ($C_6F_{12}O$), H-37, FK-5112, H-1323, H-2402, H-1301, HFC-227ea, heptafluoropropane (FM-200), and nitrogen (IG-541) have been developed. Among them, the fire extinguishing efficiency of the explosion suppressant $C_6F_{12}O$ has been fully investigated in both a laboratory burner scale and a full-scale fire extinguishing experiment. However, due to the toxic and highly corrosive thermal decomposition substances such as HF and COF_2 generated during the fire extinguishing process, it has not been widely used in engineering [59]. Through the fire extinguishing test of five traditional fluorinated chemical gases on the ancient wooden structure, it was found that the total amount of HF released was in the order of H-37 > FK-5112 > H-1323 > H-2402 > H-1301 [60]. Further comparing the ability of five new and old extinguishing agents to extinguish wood crib fire, it is found that HFC-227ea has the strongest ability to extinguish wood crib fire and will not reignited, and nitrogen (IG-541) has the best ability to dilute oxygen [61]. Therefore, HFC-227ea is considered the most suitable alternative to halon 1301 for Class A fires among the five gases. Also based on the ISO 9705 standard test, the experiment compares the ability of five fire extinguishing agents to extinguish wood crib fire, including Halon 1301, heptafluoropropane (FM-200), nitrogen (IG-541), Novec 1230, and hot aerosols. The experimental results show that FM 200 has the strongest fire suppression ability, followed by Halon 1301 and Novec 1230, respectively. However, because the latter two can only prevent the re-ignition of large wood piles, they are not suitable for small wood piles [62]. In addition, from the perspective of cultural heritage material protection and the real scene of historic building fires, studies compared the fire extinguishing efficiency of portable fire extinguishers and concluded that the following two types of fire extinguishers, HCFC blend B (Halotron I) and HFC-236fa (Fe-36), can meet the minimum requirements of UL 711. While Halotron I or FE-36 is used, immediate remediation is required to avoid rekindling and damage to cultural relics [63]. According to the SEM results of weathered wood, it can be seen in Fig. 12. (b) that the wood surface is porous and has strong gases absorption [60], and the hydrogen fluoride generated after the fire extinguishing of fluorochemical gas can deposit on the wood surface, which changes the color of the wood surface. And the content of gaseous H_2O also significantly affects the ability of HF to change color shown in Fig. 12. (a) [64]. Therefore, compared to the most commonly used Novec 1230, H-2402, H-1323, HFC-227ea, and FM-200 have stronger fire suppression and re-ignition resistance, and produce less HF, but they still cannot avoid the defects of deposition and adhesion on the wood surface.

Aerosol extinguishing technology, another emerging technology after inert gas and halon fire extinguishing agents, has attracted much attention. Aerosol technology can be further subdivided into cold aerosol technology based on dry powder or particles dispersed in solution, and hot aerosol technology forming colloids through oxidation and reduction [67]. As one of the substitutes for halon agents, the ODP and GWP values of the aerosol extinguishing agent are almost zero, which is environmentally friendly [67]. Among them, condensing aerosols can react with the flame to generate metal radicals in the application of Class A fire, and form stable compounds (such as KOH, H_2O, etc.) in the final fire extinguishing process, and then extinguish the fire, as shown in Fig. 12. (c). Moreover, due to the point shape and maintenance requirements of condensed aerosols without pipes or pressurized cylinders, they are widely used in Class A fire-fighting [65]. When comparing aerogel fire extinguishing agent with ammonium phosphate dry powder fire extinguishing agent and water-based fire extinguishing agent shown in Fig. 12. (d), it was found that the amount of aerogel fire extinguishing agent was less, the fire extinguishing time was shorter, and the cooling rate was faster in Class A standard fire extinguishing experiment. When this aerogel fire-extinguishing agent adheres to the surface of an object, due to its flame retardancy, aerogel nanoparticles can form an insulating layer to block flame and thermal radiation [66]. In order to verify the effectiveness of aerosol flame barrier and wood surface adhesion, a study compared five aerosol-forming agents (AFA) fire extinguishing efficiency tests containing phosphorus compounds named P90x and

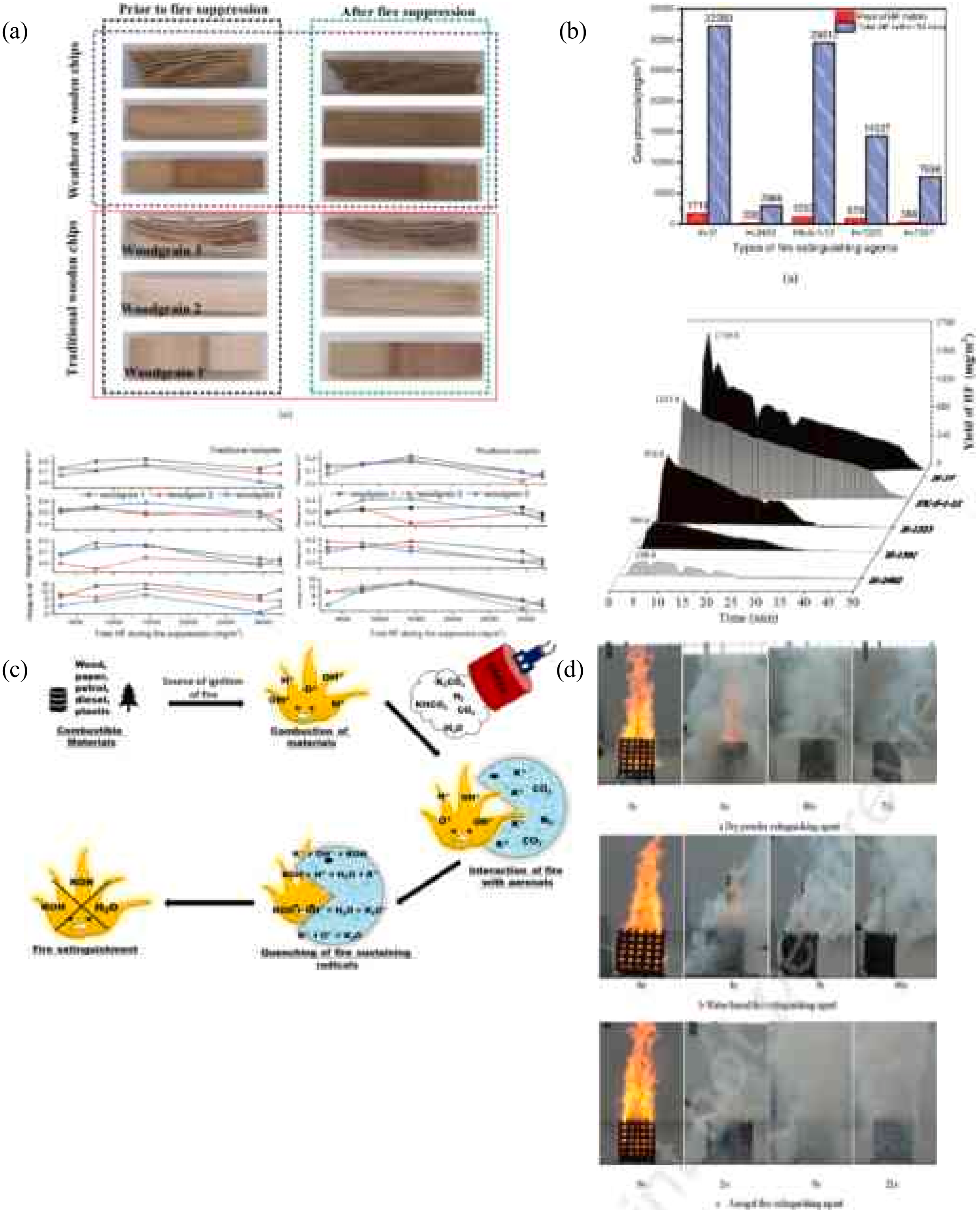


Fig. 12. (a) Color parameters change varying HF amount during fire suppression [64]. (b) The gas yield of different test conditions [60]. (c) Fire extinguishing mechanism of condensed aerosol-based fire extinguishing system [65]. (d) Wood stack fire extinguishing process with dry powder agent, water-based agent and aerogel [66].

potassium nitrate with different mass ratios, and concluded that: with the increase of P90x mass, the fire extinguishing efficiency increases, and for Class A wood stack fire, the best fire extinguishing efficiency is 20 g/m^3. Other studies have demonstrated through full-scale trials that an aerosol of an aqueous solution of potassium salt can provide a thirty-fold reduction in the flow rate of the extending fluid compared to fire suppression by pure water [68]. Therefore, in terms of aerosol, agents containing phosphides or phosphates not only have outstanding fire extinguishing efficiency, but also are harmless to the environment and less harmful to the human body. However, due to its strong adhesion and reduced fire visibility, it will damage cultural relics and affect personnel escape.

In general, both new gases extinguishing agents and aerosol technologies have been well applied to Class A fires, especially wood fires. The applications of weathered wood and open space for historic buildings are still to be developed. In summary, heptafluoropropane gas (HFC −227ea, FM-200) extinguishing agent and phosphate aerosol are currently the most efficient gas extinguishing agents with little environmental damage. While due to gas adhesion, it is bound to pose a threat to the protection of cultural relics, so future research needs to explore the restoration of cultural relics after gas extinguishing.

3.2.3. The influence of fire suppression on the surrounding environment

With the development of ecotoxicology, the impact of poisons produced by fire extinguishing on the environment has been paid more attention [69]. According to the characteristics of historic buildings using wood as the main component material, studies have shown that natural wood produces fewer toxic such as dioxins and oxides when burned than treated wood [70,71]. According to the foregoing, the following also starts from the aspects of water mist and gas extinguishing agents. As the most commonly used extinguishing medium, when using water to extinguish solid materials, the impact of fire extinguishing on the aquatic and terrestrial environment was evaluated from the perspective of ecotoxicology. And it was found that all results showed the fire extinguishing behavior had an adverse effect [72]. To carry out a more detailed assessment of environmental pollution after a fire, two models of pollutant concentration in runoff water and water and pollutant infiltration on the ground were established to slow down and inhibit the permeation of pollutants in the environment [73]. In addition, not only the fire extinguishing media will have an impact on the environment, but the extinguishing technology also will produce pollutants of varying degrees. Compared to the extinguishing technologies of water mist, high-pressure water mist, and water mist with additives, the important pollutants were separated and tested including brominated flame retardants (BFRs), organophosphorus flame retardants (OPFR), polycyclic aromatic hydrocarbons (PAHs) and linear hydrocarbons. After comparing the impact of technology on pollutant emissions shown in Fig. 13. (a), it is concluded that the pollutants released by high-pressure water systems were the least, but the impact on the wood surface is more serious [74]. In terms of gas flame retardants, brominated and antimony-containing flame retardants are the main causes of the increasing production of CO and hydrogen cyanide (HCN) [75]. Phosphorus-, inorganic and nitrogen-containing flame retardants are less environmentally harmful than haloalkanes and antimony-containing flame retardants and have stronger friendliness and safety. It has also been shown that dioxins and furans are formed if organic substances coexist with chlorine or bromine during combustion [76]. In terms of gas extinguishing agents, hydrofluorocarbons (HFCs) are gradually becoming an alternative to chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Although most HFCs are low or non-flammable, they still can form flammability in fire situations where temperature and pressure elevate. In addition to flammability risks, HFCs are subject to hazards such as global warming and exposure to ecotoxicity [77]. Fire foam, which is also used as a fire extinguishing agent, will also cause environmental pollution after putting out a fire. It is a recognized fact that the ingredients in fire foam foaming agents, including ethylene glycol, butyl ethylene glycol, propylene glycol, alkylpolyglycoside, and nonyl alcohol, will lead to the toxicity of the substance. This is mainly due to the poor biodegradability of the decomposition products of foaming agents, which can enter the soil or rivers with media such as water, thus affecting the purification of water, biology, and waste purification [78]. In general, both water mist fire extinguishing technology and gas fire extinguishing technology will have irreversible effects on the environment, including river or

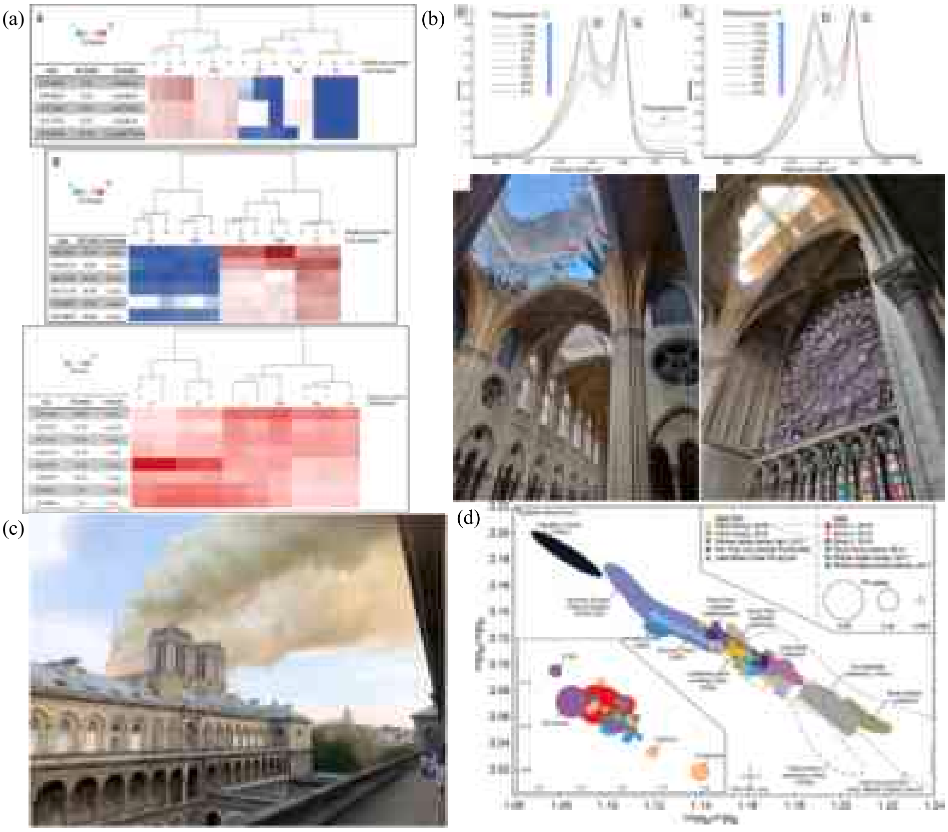


Fig. 13. (a) Dendrogram and selected heatmap for gas samples from five fire tests to compared to the four extinguishing technologies [74]. (b) Raman spectra of experimental charcoals obtained from oak wood with the carbonization temperature. And the openings in the vault show carbonized oak beams and the steel scaffolding deformed by the high temperatures [79]. (c) The fire at Notre Dame as seen from the Hotel-Dieu hospital [80]. (d) Lead isotope plot for all honey [81].

groundwater pollution, atmospheric or ozone layer destruction, etc.

In the world-renowned Notre Dame Cathedral, serious environmental pollution was caused due to the role of the structure and extinguishing means. Because the cover of the cathedral was made of hundreds tons of lead on large oak beams, this fire corresponds to a large forest with an area of nearly 1700 m^2 [82]. A study determined that the highest temperature of the roof structure area in the fire was measured by a Raman paleothermometer. It is found that the maximum temperature reaches 1212 ± 79℃, which is much higher than the melting point of lead, 327℃, and lower than its evaporation temperature, 1740℃, seen from Fig. 13. (b) [79]. This illustrates a large amount of lead melting in the event of the fire, as evidenced by the re-solidification of the lead flow on the walls. The lead contamination found in the area around the church was also attributed to lead in aerosol form or lead oxides, rather than lead evaporation [82]. In the process of firefighting, a large amount of lead-containing sewage was discharged into the Seine River not far from the church under the scouring effect of water. As yellow smoke containing lead oxide forms, it was dispersed with the fire plume and eventually settled down shown in Fig. 13. (c) [80]. After the fire, the lead dust concentration in Paris, not only the church and the square in front of it, was at a high level beyond the normal range for a long time [12]. The air and soil near the accident site and the area where the diffusion plume may reach were sampled and analyzed. Some studies assess the post-accident environment by analyzing the honey production in flue gas diffusion areas and plot lead deposition seen from Fig. 13. (d) [81]. From any point of view, about 450 tons of lead spread to the church by fire [83] and concentrated in the ruins, which is bound to have a profound impact on the surrounding environment. Although the material of the ancient building itself has played a role in the environmental impact from the fire extinguishing of Notre Dame Cathedral, the selection of firefighting means and extinguishing medium determines environmental pollution in essence.

3.3. Restoration after fire suppression

In the event of a fire in a historic building, the whole or part of the building will be damaged that cannot be completely restored. However, according to the basic principle of traditional cultural relics restoration, repairing the old as the old, whether it is equivalent reconstruction or contemporary redesign, the buildings need to be examined first. According to the fact that the wooden components are usually damaged on the cross-section exterior part and the inner part is non-damaged after the fire, an auxiliary injury detection method based on the combination of laser scanner and drilling resistance tests was proposed. This method has been successfully applied to Portuguese historical buildings to carry out the structural safety assessment and health monitoring on damaged

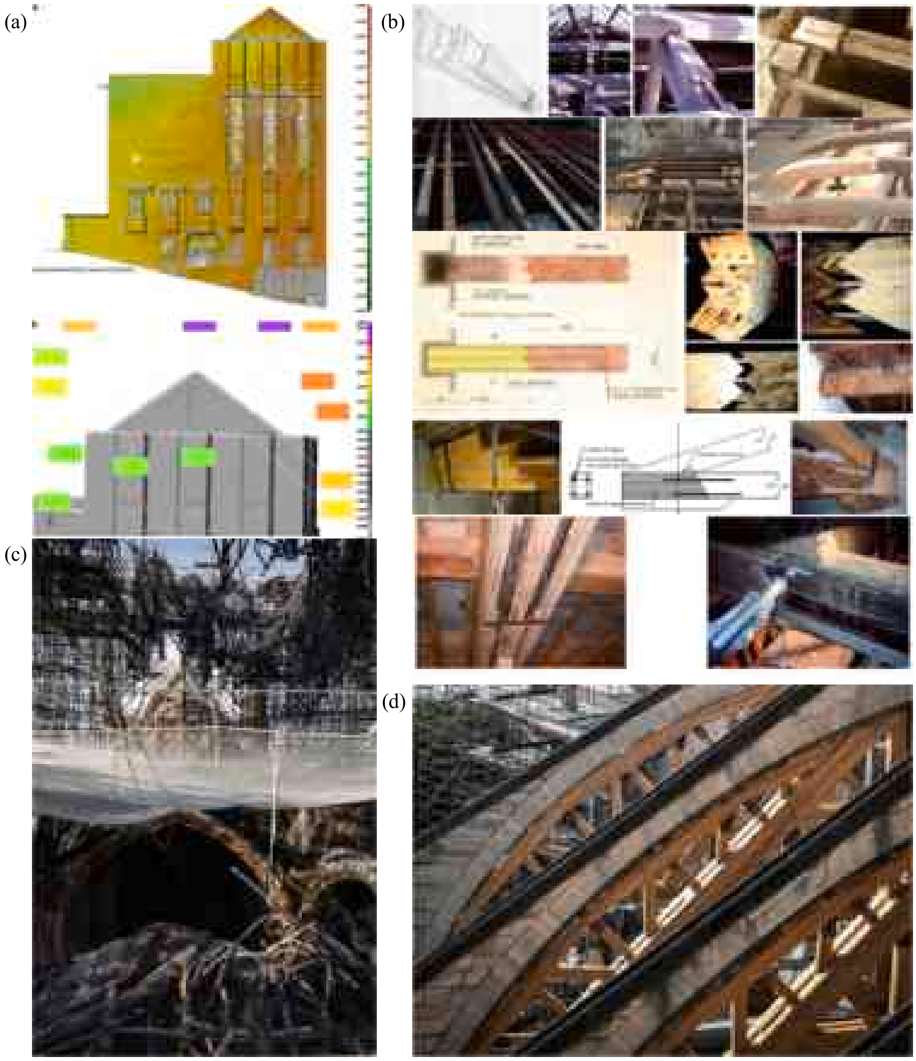


Fig. 14. (a) Quantitative monitoring of the west facade of Mackintosh building using laser scanning data before and after the fire [86]. (b) Reinforce wood with steel plates, steel rods, logs, and resins, including Valentino Castle (seventeenth century), Torino, Italy, and Rinoji Temple in Japan [88,89]. (c) Wooden vault support and metal net covering suspension adopted after Notre Dame fire [12,87].

wooden beams, and a three-dimensional numerical model was provided for the later restoration [84]. After a comprehensive understanding of the extent of damage, it is necessary to determine the restoration plan, followed by structural reinforcement and fire protection work respectively. In the process of formulating the restoration plan, Libušín, an all-wood object, was used as an example to use BIM software for 3D modeling, which helped to determine the method of using traditional techniques to restore and reconstruct the entire structure with only 12 % of the original structure after the fire [85]. Moreover, as shown in Fig. 14. (a), 3D digital document technology can provide quantitative data for the repair and artistic aesthetic treatment after fire [86]. After the analysis and evaluation of the structural stability and collapse possibility of the Notre Dame Cathedral, the aging wood that ensures the bearing load should be used as a substitute for the repair to be closer to the original appearance of the building [87].

In the actual repair and reconstruction phase, a relatively complete structural shell is a prerequisite for reconstruction and restoration. When the degree of fire damage is too high will directly affect the possibility of reconstruction, for example, the damage of Clandon Park reached 95 % [90], so its reconstruction and final design scheme have been repeatedly considered. The same situation also occurred in the Södra Råda wooden church in Sweden, which was built in the Middle Ages. Only some charred wooden beams were left at the time of the 2001 fire, making the reconstruction project to be completed by the end of 2018 [91]. Secondly, restoring the original structure and enhancing its fire protection capacity have become the two major centers of the work. In terms of structural reinforcement, the method of adding steel beams is used to improve the stability and strength of the overall structure shown in Fig. 14. (b). Near Grantham in Lincolnshire, Stoke Rochford Hall made minor modifications to the original building, adding steel beams and replacing the ceiling with fiber plaster to reduce floor loads [92]. In restoration projects, fire prevention is equally important. This is mainly because there was a second fire during the repair work. The Mackintosh Building, Glasgow School of Art, had another fire in 2018, the third year of the first fire repair. This fire was larger than the first fire and caused more extensive damage to the building [93] that almost all of the wooden structures were burned out in the fire. The Cathedral Church of St Peter, York Minster, built in the early 13th century, replaced the vaulted web and covered it with fire-retardant plaster and metal mesh to improve fire performance [91]. As shown in Fig. 14. (c), Notre Dame Cathedral also chooses the form of metal mesh and vault support to help the post disaster repair of buildings.

As a significant part of the restoration work, the protection of cultural relics depends on the rescue of the fire remains to a large extent. During the fire at Uppark, which benefited from the salvage of the fire debris, most of the precious collection was successfully preserved [10].

In general, in the stage of damage assessment, scheme determination, and reinforcement and fire prevention of historic building restoration, ultrasonic, microwave, and laser non-destructive testing methods, 3D digital technology, steel frame auxiliary support structure and fire-retardant covering materials are the most commonly used and advanced technologies. And these technologies can ensure that the original damaged building is not damaged as much as possible. In terms of the emergency repair of cultural relics, the salvage plays a decisive role.

4. Prospect

Although the current research on ancient building fires has achieved multi-latitude phased results, there are still many directions worthy of further study. To protect ancient buildings from fire damage in the longer term, more new technologies can be applied to the scene laying a good foundation for technology development and leaving sufficient space for technological expansion. In terms of fire detection and early warning, early warning materials, image monitoring, identification, and wireless networking are the main research hotspots at present, and more attention can be paid to large-area coverage, interference filtering, intelligent algorithms, and green energy-saving. In terms of fire extinguishing technology, both fine water mist and gas extinguishing agents should first follow the principle of minimal damage to the building, and secondly, the best extinguishing efficiency of additives, the flexibility of extinguishing equipment, and environmental harmlessness still need to be further studied. In terms of post-disaster restoration, due to the lack of statistical analysis of post-disaster building stability and other properties, the variety of reinforcement materials and rescue fire prevention measures that can be used in actual restoration still need to be explored.

5. Conclusions

In recent years, with the frequent occurrence of historical building fires, research in this field has also received more attention and made remarkable progress. On the one hand, this paper analyzes the fires in China, and on the other hand, reviews the research on fire prevention and extinguishment. For the above results and discussion, the conclusions can be summarized as followings:

(1) Affected by the Qingming Festival and Spring Festival, fires mostly occur in January, April, November, and December, concentrated in spring and winter. Through gray correlation analysis, the cause and damage of fire are further analyzed, and it can be concluded that electrical factors, careless use of fire, and arson are the most important three factors.
(2) The typical wooden historical building fire is described by using four fire cases. By describing the occurrence and development of four cases in Gong Chen Lou, Du Ke Zong ancient city, Falun Temple, and Zheng Ding ancient city gate, the causes and serious consequences of the fire are emphasized. This provides a reference for fire prevention of historic buildings in the world, and also fills the research gap in the field of ancient building fires in China.
(3) From the perspective of detection and early warning, the research progress of fire prevention and control in historic buildings is reviewed. The coating materials represented by MXene and GO have the characteristics of flame retardancy, smoke suppression, signal transmission and weathering resistance, which improves the sensitivity and long-term monitoring ability of fire disposal for wood combustion. Neural network algorithm, wireless sensing and Internet of Things (IoT) networking technology can provide a visual regional fire management system for historic buildings, and intelligently judge the fire phenomenon under the interference of incense burning factors.
(4) Present research progress and future research direction of fire extinguishing technology applicable to ancient buildings are introduced and prospected. For water mist, MC additive and potassium salt additives represented by K_2CO_3 have high fire extinguishing efficiency, simple preparation and little environmental impact, which are effective to extinguishing wood fires in historic buildings. The inert gas drive system dominated by nitrogen and the way of full jet and spray jet can further reduce the oxygen content in the fire site and improve the cooling capacity of the water mist. For gas extinguishing agents, heptafluoropropane and phosphate aerosols are currently the most effective extinguishing agents to suppress historic building fires. In the future, it is necessary to conduct in-depth research on the control and prevention of firefighting water seepage polluting rivers and groundwater, and the removal of gas residues attached to cultural relics, in order to reduce the impact of fire extinguishing on the environment.
(5) The process and key points of post-fire reconstruction of ancient buildings is reviewed. According to the three stages of damage assessment, scheme determination, and reinforcement and fire prevention in the repair process, laser non-destructive testing,

BIM, and 3D digital modeling can assess the safety degree of damaged wooden structures, determine the possibility of building collapse, reinforcement and repair steps without damaging the building itself. In the actual reconstruction and restoration, the addition of steel frame auxiliary support and the covering of flame-retardant material on the fire surface is the most effective for wooden historic buildings. In terms of cultural relics protection, emergency salvage after disasters is a rescue work that plays a fundamental role.

CRediT authorship contribution statement

Biao Zhou: Supervision. **Chenyang Jiang:** Writing – original draft. **Kai Wang:** Software, Resources. **Xavier Romão:** Formal analysis, Conceptualization. **Hideki Yoshioka:** Writing – review & editing, Visualization, Validation. **Wei Wang:** Writing – review & editing, Software. **Zhenxiang Tao:** Writing – review & editing, Writing – original draft. **Haixia Zhao:** Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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